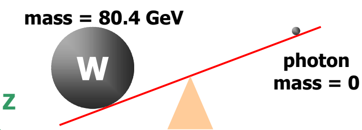
The Higgs Mechanism

- In the Standard Model
  - Electroweak symmetry breaking occurs through introduction of a scalar field $\phi \rightarrow$ masses of W and Z
  - Higgs field permeates space with a finite vacuum expectation value = 246 GeV
  - If ϕ also couples to fermions $\rightarrow$ generates fermion masses

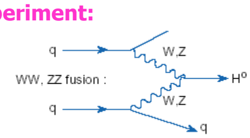


- An appealing picture: is it correct?
  - One clear and testable prediction: there exists a neutral scalar particle which is an excitation of the Higgs field
  - All its properties (production and decay rates, couplings) are fixed except its own mass

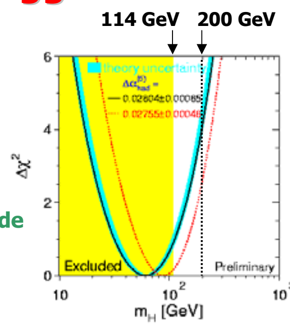
Highest priority of worldwide high energy physics program: find it!

God particle disappears down £6billion drain

- This field need not result from a single, elementary, scalar boson
  - There can be more than one particle
    - e.g. SUSY
  - Composite particles can play the role of the Higgs
    - e.g. technicolor, topcolor
- We do know that
  - EW symmetry breaking occurs, so something is coupling to the W and Z
  - Precision EW measurements imply that this thing looks very much like a Standard Model Higgs
    - though its fermion couplings are less constrained
  - WW cross sections violate unitarity at ~ 1 TeV without H
    - A real LHC experiment:



Searching for the Higgs



- **Over the last decade, the focus has been on experiments at the LEP e^+e^- collider at CERN**
  - precision measurements of parameters of the W and Z bosons, combined with Fermilab's top quark mass measurements, set an upper limit of $m_H \sim 200$ GeV
  - direct searches for Higgs production exclude $m_H < 114$ GeV
- **Summer and Autumn 2000: Hints of a Higgs?**
  - the LEP data may be giving some indication of a Higgs with mass 115 GeV (right at the limit of sensitivity)
  - despite these hints, CERN management decided to shut off LEP operations in order to expedite construction of the LHC

"The resolution of this puzzle is now left to Fermilab's Tevatron and the LHC."
– Luciano Maiani

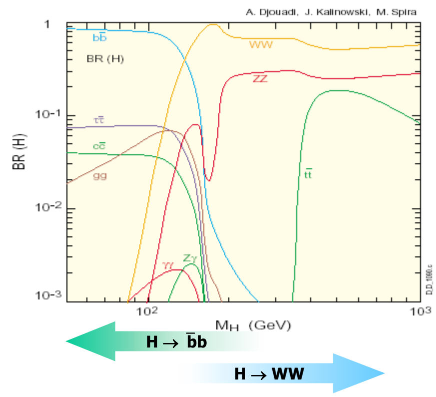
Higgs at the Tevatron

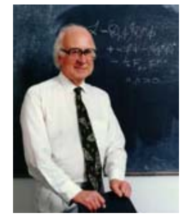
- **The search for the mechanism of EWSB motivated the construction of supercolliders (SSC and LHC)**

- **After the demise of the SSC, there was a resurgence of interest in what was possible with a "mere" 2 TeV**
  - Ideas from within accelerator community ("TeV33")
  - Stange, Marciano and Willenbrock paper 1994
  - TeV2000 Workshop November 1994
  - Snowmass 1996
  - TeV33 committee report to Fermilab director
  - Run II Higgs and Supersymmetry Workshop, November 1998
- **A convergence of**
  - technical ideas about possible accelerator improvements
  - clear physics motivation
    - Plan for integrated luminosities, before LHC turn-on, much larger than the (then) approved 2fb^{-1}

Higgs decay modes

- The only unknown parameter of the SM Higgs sector is the mass
- For any given Higgs mass, the production cross section and decays are all calculable within the Standard Model

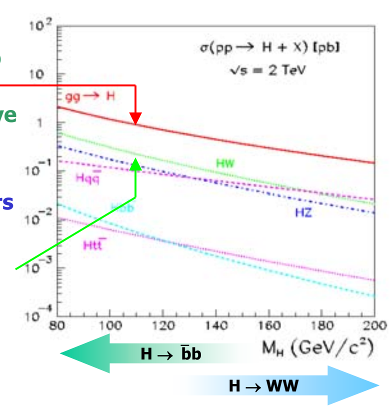




One Higgs

Higgs Production at the Tevatron

- Inclusive Higgs cross section is quite high: ~ 1pb
  - for masses below ~ 140 GeV, the dominant decay mode H → bb is swamped by background
  - at higher masses, can use inclusive production plus WW decays
- The best bet below ~ 140 GeV appears to be associated production of H plus a W or Z
  - leptonic decays of W/Z help give the needed background rejection
  - cross section ~ 0.2 pb

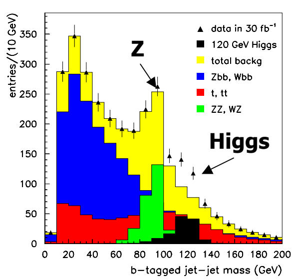


Dominant decay mode

$m_H \lesssim 140$ GeV: $H \to b\bar{b}$

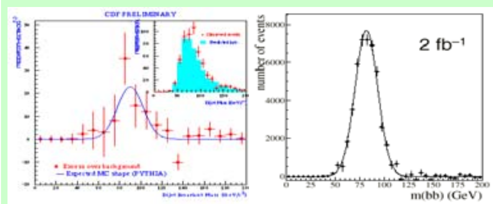
- $WH \to q\bar{q}' b\bar{b}$ is the dominant decay mode but is overwhelmed by QCD background
- $WH \to l^{\pm}\nu b\bar{b}$ backgrounds $Wb\bar{b}$, WZ, $t\bar{t}$, single top
- $ZH \to l^{+}l^{-} b\bar{b}$ backgrounds $Zb\bar{b}$, ZZ, $t\bar{t}$
- $ZH \to \nu\nu b\bar{b}$ backgrounds QCD, $Zb\bar{b}$, ZZ, $t\bar{t}$
  - powerful but requires relatively soft missing E_T trigger (~ 35 GeV)

$m_H = 120$ GeV



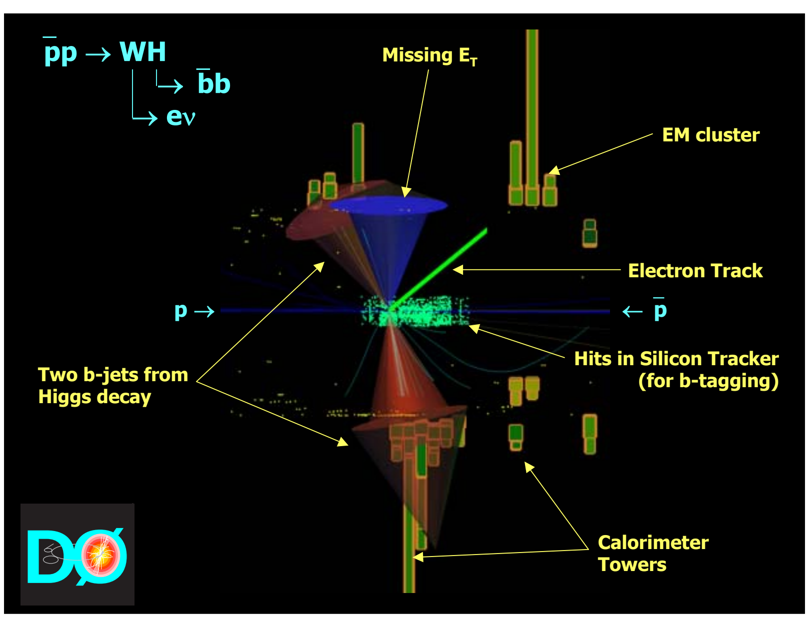
$2 \times 15\text{fb}^{-1}$ (2 experiments)

$b\bar{b}$ mass resolution
Directly influences signal significance
$Z \to b\bar{b}$ will be a calibration



CDF $Z \to b\bar{b}$ in Run I

DØ simulation for 2fb^{-1}



Example: m_H = 115 GeV

- ~ 2 fb^{-1}/expt (2003): exclude at 95% CL
- ~ 5 fb^{-1}/expt (2004-5): evidence at 3σ level
- ~ 15 fb^{-1}/expt (2007): expect a 5σ signal

Every factor of two in luminosity yields a lot more physics

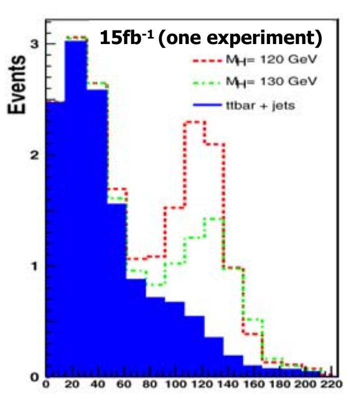
- Events in one experiment with 15 fb^{-1}:

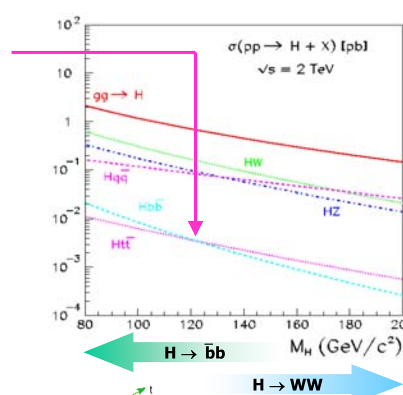
Mode	Signal	Background	S/√B
l νbb	92	450	4.3
ννbb	90	880	3.0
l l bb	10	44	1.5

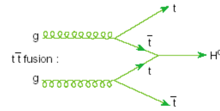
- If we do see something, we will want to test whether it is really a Higgs by measuring:
  - production cross section
  - Can we see H → WW? (Branching Ratio ~ 9% and rising w/ mass)
  - Can we see H → ττ? (Branching Ratio ~ 8% and falling w/ mass)
  - Can we see H→ γγ? (not detectable for SM Higgs at the Tevatron)

Associated production $t\bar{t}$ + Higgs

- Cross section very low (few fb) but signal:background good
- Major background is $t\bar{t}$ + jets
- Signal at the few event level:







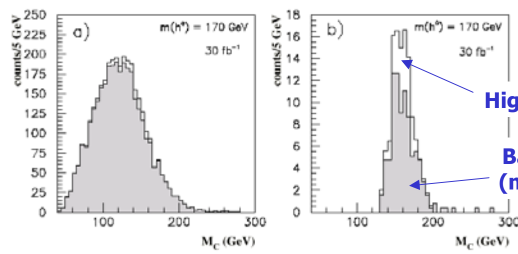
Tests top quark Yukawa coupling

$m_H \gtrsim 140$ GeV : $H \to WW^{(*)}$

- $gg \to H \to WW^{(*)} \to l^+l^- \nu\nu$

  Backgrounds Drell-Yan, WW, WZ, ZZ, tt, tW, $\tau\tau$
  Initial signal:background ratio ~ 10^{-2}

  - Angular cuts to separate signal from "irreducible" WW background



$2 \times 15\text{fb}^{-1}$
(2 experiments)

Higgs signal

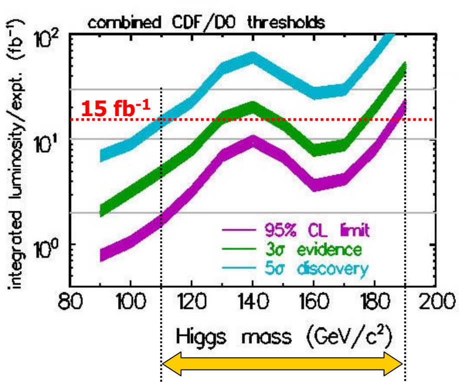
Background
(mainly WW)

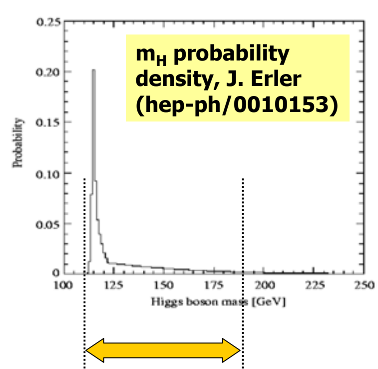
Before tight cuts:
verify WW modelling

After tight cuts

M_C = *cluster transverse mass* $= \sqrt{p_T^2(\ell\ell) + m^2(\ell\ell)} + \not{E}_T$

Tevatron Higgs mass reach





110-190 GeV

No guarantee of success, but certainly a most enticing possibility

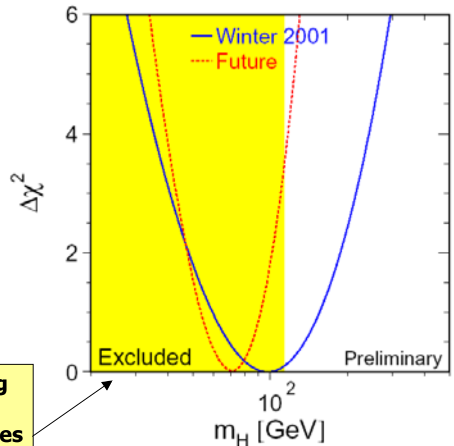
Indirect Constraints on Higgs Mass

- Future Tevatron W and top mass measurements, per experiment

	Δm_W
2 fb^{-1}	±27 MeV
15 fb^{-1}	±15 MeV

	Δm_t
2 fb^{-1}	±2.7 GeV
15 fb^{-1}	±1.3 MeV

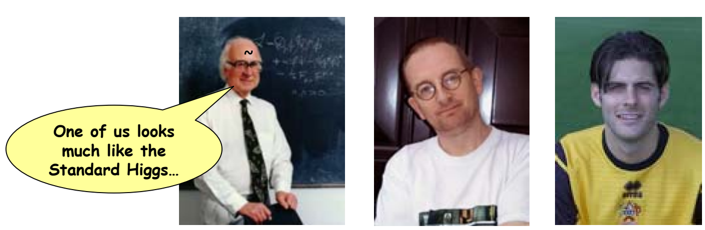
Impact on Higgs mass fit using Δm_W = 20 MeV, Δm_W = 1 GeV, $\Delta\alpha = 10^{-4}$, current central values
M. Grünewald et al., hep-ph/0111217



Supersymmetric Higgs sector

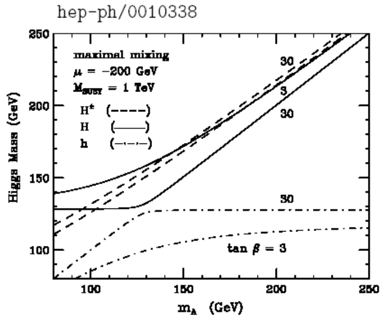
- Expanded Higgs sector: h, H, A, $H^\pm$
- Properties depend on
  - At tree level, two free parameters (usually taken to be m_A, tan β)
  - Plus radiative corrections depending on sparticle masses and m_t

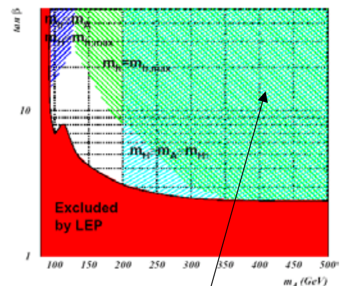
Multiple Higgses



Supersymmetric Higgs Masses

hep-ph/0010338





Over much of the remaining allowed parameter space,
m_h ~ 130 GeV,
$m_A \sim m_H \sim m_{H\pm}$ = "large"

<u>From LEP:</u>
m_h > 91 GeV, m_A > 92 GeV, $m_{H\pm}$ > 79 GeV, tanβ > 2.4

MSSM Higgs Decays

Very rich structure!

For most of allowed mass range h behaves very much like H_{SM}
- H → WW and ZZ modes suppressed compared to SM
- bb and ττ modes enhanced

A → $\bar{b}$b and ττ

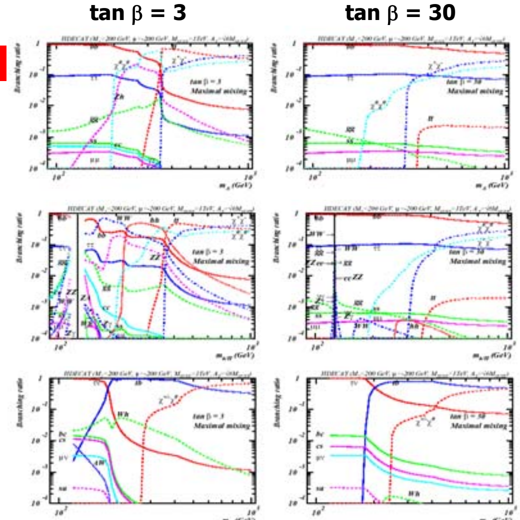
H± → τν and $\bar{t}$b

tan β = 3 **tan β = 30**

h, H

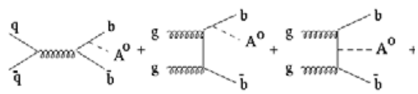
A

H±



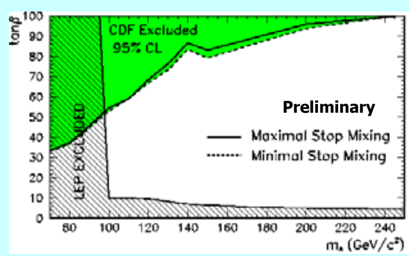
SUSY Higgs Production at the Tevatron

- bb(h/H/A) enhanced at large tan β:

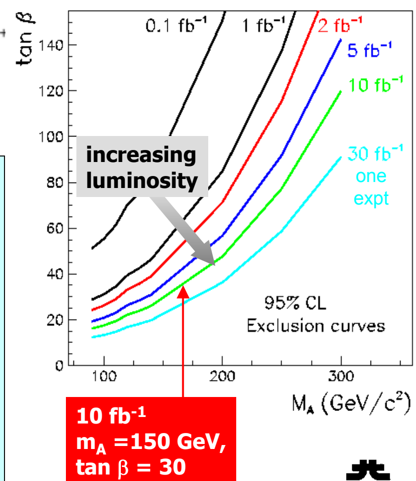


- $\sigma \sim 1$ pb for tanβ = 30 and m_h = 130 GeV

CDF Run 1 analysis (4 jets, 3 b tags) sensitive to tan β > 60

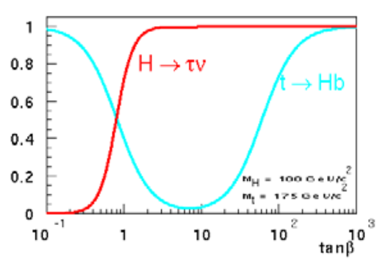


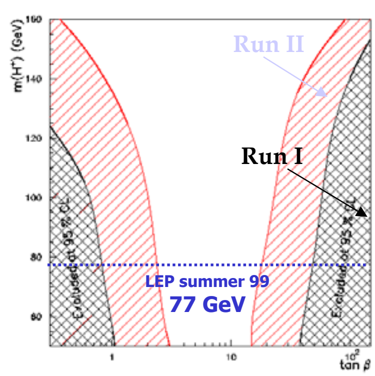
bb(h/A) → 4b



Charged Higgs

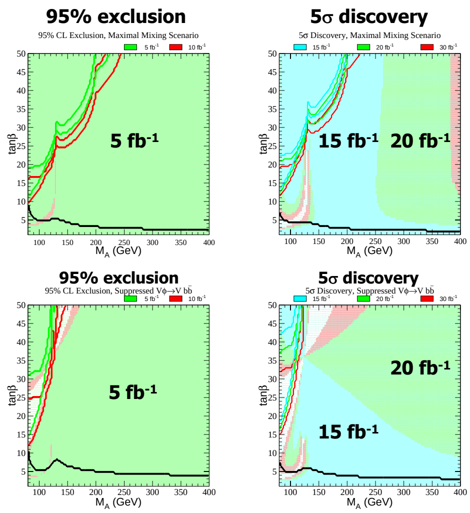
- Tevatron search in top decays
- Standard tt analysis, rule out competing decay mode $t \to H^{\pm}b$
- Assumes 2 fb^{-1}, n_{obs} = 600, background = 50 ± 5





- LEP not really sensitive to MSSM region (expect m_H > m_W)

SUSY Higgs reach at the Tevatron



Luminosity per experiment, CDF + DØ combined

Exclusion and discovery for maximal stop mixing, sparticle masses = 1 TeV

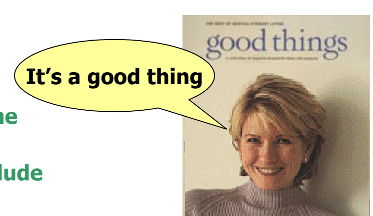
Most challenging scenario: suppressed couplings to bb

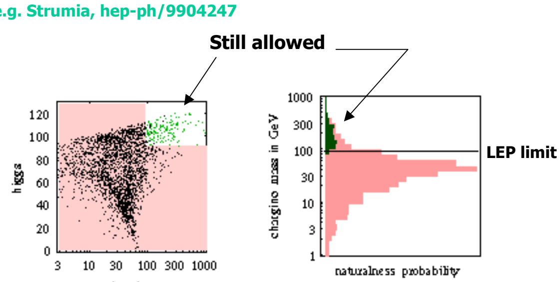
Enhances $h \to \gamma\gamma$?

John Womersley

What if we see nothing?

- As long as we have adequate sensitivity, exclusion of a Higgs is still a very important discovery for the Tevatron
  - In the SM, we can exclude most of the allowed mass range
  - In the MSSM, we can potentially exclude <u>all</u> the remaining mass range
    - A light Higgs is a very basic prediction of the supersymmetric SM
    - e.g. Strumia, hep-ph/9904247





John Womersley

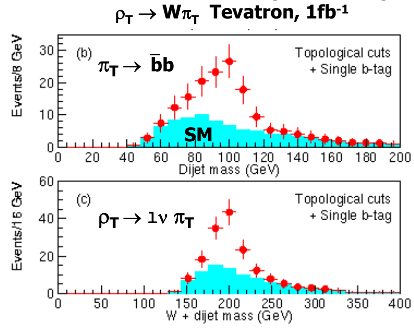
What if we see something else?

- **Alternatives to SUSY: dynamical models like technicolor and topcolor**
  - **the Higgs is a composite particle: no elementary scalars**
  - **many other new particles in the mass range 100 GeV - 1 TeV**
  - **with strong couplings and large cross sections**
  - **decaying to vector bosons and (third generation?) fermions**

At the Tevatron, you have to be lucky, but if you are, you can win big:

"MTSM" Technicolor (Lane et al.,)

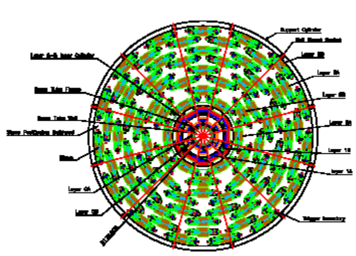
$\rho_T \to W\pi_T$ Tevatron, 1fb^{-1}



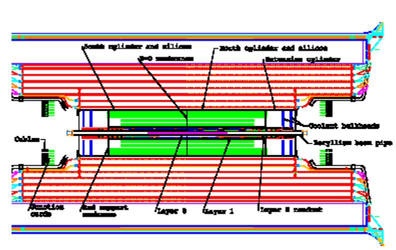
John Womersley

Run 2B

- **Planning has started on the additional detector enhancements that will be needed to meet the goal of accumulating 15 fb^{-1} by end 2007**
  - **major components are two new silicon detectors to replace the present CDF and DØ devices which can not survive the radiation dose**
  - **Technical design reports submitted to the laboratory Oct 2001**
  - **goal: installed and running by early 2005**



Proposed DØ Run 2B silicon detector

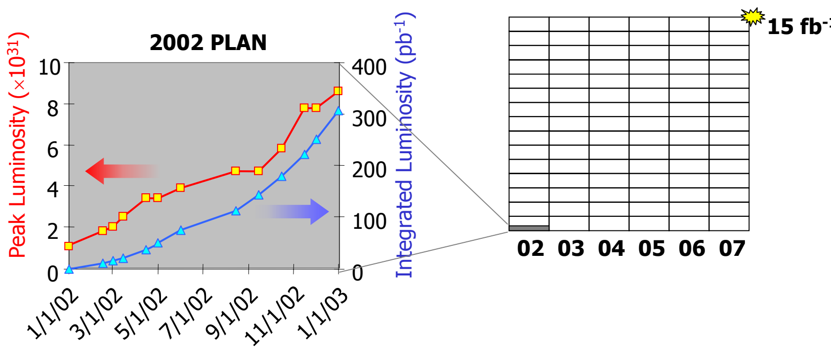


Run 2B silicon installed

John Womersley

Tevatron plan for 2002

- Only ~ 20pb^{-1} delivered so far, which CDF and DØ have used to commission their detectors
- 2002 will be the year that serious physics running starts



What will we know and when will we know it?

- By 200x at the Tevatron, if all goes well
  - We will observe a light Higgs
    - Test its properties at the gross level
    - but not able to differentiate SM from MSSM
  - <u>Or</u> we will exclude a light Higgs
    - Interesting impact on SUSY
  - We will tighten exclusion regions for MSSM charged Higgs and multi-b jet signals at high tan β
  - We may even be lucky enough to find something else
    - e.g. low scale technicolor

Top ten reasons to pursue the Higgs search at Fermilab

10. Window of opportunity before LHC startup is not getting shorter
9. The origin of EWSB has been unclear for way too long, and theorists can't figure the question out by themselves
8. Find it while Mr. Higgs is still alive and can win the Nobel Prize
7. Learn if there really are fundamental scalars (SUSY?)
6. Learn why the standard model seems to work so well
5. We might find something other than a Higgs
4. Excluding a light Higgs is almost as interesting as finding it
3. Huge potential payback for a (relatively) small investment
2. Excitement and discovery move the field forward
1. Because we can!

A three-stage relay race

- Tevatron
  - Discovery if we're lucky
    - Fermilab's role is obvious
- LHC
  - Guaranteed discovery of one or more Higgs or some other signal of EWSB
  - Measure properties at the 20% level
  - Learn a lot more about physics at the TeV scale (SUSY? Extra dimensions?)
    - Fermilab's role is significant but needs to be consolidated for the physics analysis phase
- Linear Collider
  - Measure, measure, measure:
    Higgs couplings to W, Z, individual fermions, HHH coupling
    - What is Fermilab's role?

What the Higgs search will teach us

- What is the source of mass of the W and Z?
  - Why is the weak force weak?
- What is the source of mass of the fundamental fermions?
- Are there fundamental scalars?
- Is there SUSY?
  - if no light Higgs, no weak scale SUSY…
- Is there other new physics at the weak scale?
  - New forces like technicolor
  - Are m_W, m_t and m_H consistent with precision EW fits?
- What is the mass scale of new physics?
- What is the next machine we'll want to build after the linear collider?

What the Higgs search won't explain

- Why fermion masses have the values they do
  - Why is the top quark so heavy?
- The origin of all mass in the universe
  - The universe is roughly
    - 70% dark energy (???)
    - 20% cold dark matter
      - e.g. neutralinos with mass ~100 GeV
    - 5% neutrinos?
    - 5% baryons
      - whose mass is almost all due to QCD
- Flavor
  - What distinguishes a top quark from an up quark?

Supersymmetry searches

- **Supersymmetry predicts multiple Higgs bosons, strongly interacting squarks and gluinos, and electroweakly interacting sleptons, charginos and neutralinos**
  - **masses depend on unknown parameters, but expected to be 100 GeV - 1 TeV**

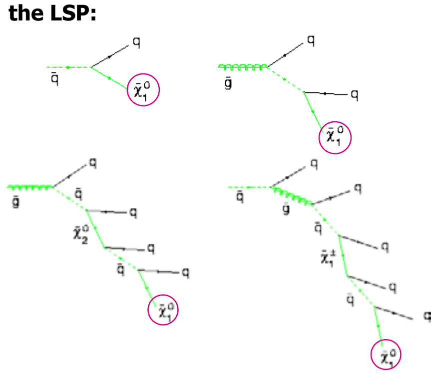
Direct searches all negative so far

- **LEP**
  - **squarks (stop, sbottom) > 80-90 GeV**
  - **sleptons (selectron, smuon, stau) > 70-90 GeV**
  - **charginos > 70-90 GeV**
  - **lightest neutralino > 36 GeV**
- **Tevatron Run I**
  - **squarks and gluinos**
  - **stop, sbottom**
  - **charginos and neutralinos**

Supersymmetry signatures

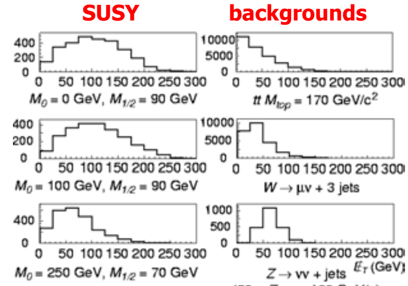
- **Squarks and gluinos are the most copiously produced SUSY particles**
- **As long as R-parity is conserved, cannot decay to normal particles**
  - **missing transverse energy from escaping neutralinos (lightest supersymmetric particle or LSP)**

Possible decay chains always end in the LSP:



Missing E_T

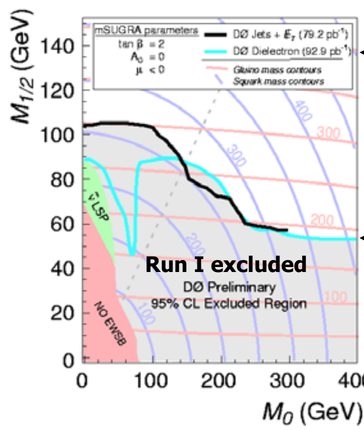
SUSY **backgrounds**



Search region typically > 75 GeV

Run 1 search for squarks and gluinos

- Two complementary searches
  - jets plus missing E_T and no electrons/muons
  - 2 electrons, 2 jets + Missing E_T

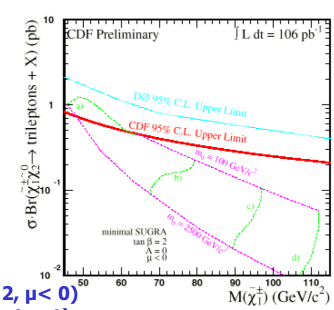


Reach with 2 fb^{-1}:
gluino mass ~ 400 GeV

Run I reach
gluino ~ 200 GeV
squark ~ 250 GeV

Chargino/neutralino production

- "Golden" signature: three leptons
  - very low standard model backgrounds
- This channel was searched in Run 1, but limits not competitive with LEP
  - however, becomes increasingly important as squark/gluino production reaches its kinematic limits (masses 400-500 GeV)



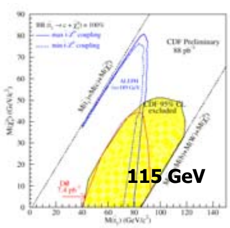
- Run II reach on $\chi^{\pm}$ mass ~ 180 GeV (tan β = 2, μ< 0)
  ~ 150 GeV (large tan β)
- Challenges
  - triggering on low momentum leptons
  - how to include tau leptons?

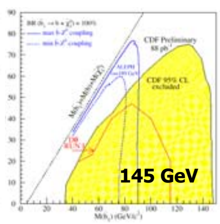
It is quite conceivable that we discover SUSY in this mode before we find the Higgs!

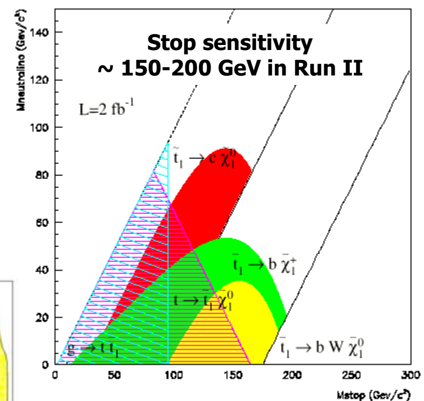
Stop and Sbottom

- Often the SUSY partners of b and t are the lightest squarks
- Stop
  - stop $\to$ b + chargino or W (top like signatures)
  - stop $\to$ c + neutralino
  - top $\to$ stop and gluino $\to$ stop
- Sbottom
  - 2 acollinear b-jets + E_T^{miss}

CDF Run I stop and sbottom limits



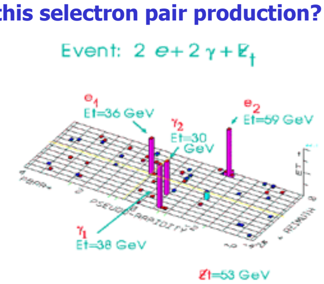


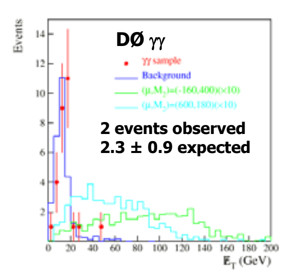


Sbottom sensitivity ~ 200 GeV in Run II

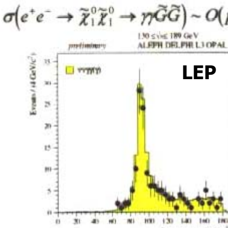
Has SUSY been discovered?

- Is this selectron pair production?





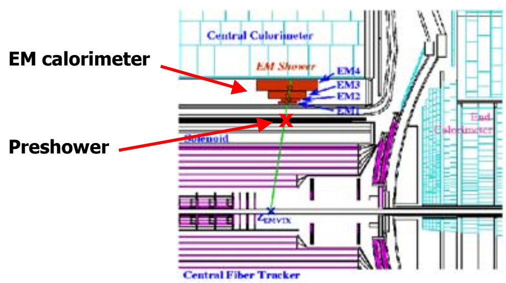
$$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma\tilde{G}\tilde{G}) \sim O(pb)$$



- All we can say is that searches for related signatures have all been negative
  - CDF and DØ $\gamma\gamma$ + missing E_T
  - DØ γ + jets + missing E_T
  - LEP

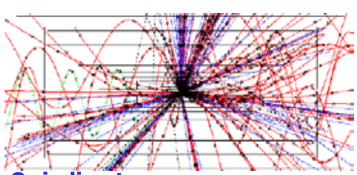
Gauge mediated SUSY

- Standard benchmark is so-called "minimal supergravity inspired" (mSUGRA) models — but other scenarios for SUSY breaking give other signatures
- e.g. Gauge mediated SUSY:
  - lightest neutralino decays to a photon plus a gravitino, maybe with a finite path length
- Run 2 DØ direct reconstruction with σ_z = 2.2 cm, σ_r = 1.4 cm



TeV-scale gravity

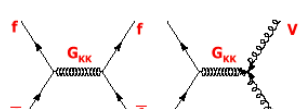
- Observable effects can be direct and spectacular . . .

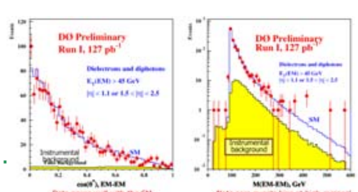


Production of Black Holes may even occur

Decay extremely rapidly (Hawking radiation) with spectacular signatures

- Or indirect . . .
  - DØ Run 1 limits from virtual graviton effects on e^+e^- and $\gamma\gamma$ production (1.0 - 1.3 TeV for 2-7 extra dimensions, ADD)





  - Prospects for Run 2: 1.5 - 2.5

Sleuth

- A new approach from DØ: attempt at a model-independent analysis framework to search for new physics
  - will never be as sensitive to a particular model as a targeted search, but open to anything
  - searches for deviations from standard model predictions
- Systematic study of 32 final states involving electrons, muons, photons, W's, Z's, jets and missing E_T in the DØ Run 1 data
- Only two channels with some hint of disagreement
  - 2 electrons + 4 jets
    - observe 3, expect 0.6± 0.2, CL = 0.04
  - 2 electrons + 4 jets + Missing E_T
    - observe 1, expect 0.06±0.03, CL = 0.06
- While interesting, these events are not an indication of new physics, given the large number of channels searched
  - 89% probability of agreement with the Standard Model (alas!)

This approach will be extremely powerful in Run 2

Quaero

- DØ has now largely completed the analysis of Run 1 data
- We have therefore decided to make a number of well-understood Run 1 data sets publicly available through a web interface

http://quaero.fnal.gov

- This is a new direction for high energy physics
- Please try it!
  - For details see hep-ex/0106039

The scientific record to date

CDF (1988-2002)

- Publications from Run I and earlier
  - 158 articles in Physical Review Letters
  - 82 in Physical Review
  - 61 in Nuclear Instruments and Methods
- 24 of these publications have over 100 citations in the SPIRES database
  - 6 papers on the top quark, including the two papers on the discovery which each have over 500 citations.
  - 7 on QCD, 5 on W and Z bosons, 2 on Supersymmetry searches, 1 on other exotic searches, 1 on CP violation and 2 on instrumentation
  - This is more highly cited results than any other HEP experiment.
- 188 Ph.D. theses completed

D0 (1994-2002)

- Publications from Run I
  - 69 articles in Physical Review Letters
  - 14 in Physics Letters
  - 31 in Physical Review
  - 38 in Nuclear Instruments and Methods
- 5 of these publications have over 100 citations in the SPIRES database
  - 2 top quark papers, including the discovery paper with over 500 citations
  - 1 on a Supersymmetry search, 1 on QCD, and 1 on instrumentation
- 128 Ph.D. theses completed

Physics prospects for Run 2

100 pb^{-1}

- measure first W, Z, jet, top, b, cross sections at 1.96 TeV
- start B-physics program

300 pb^{-1}

- pin down high-E_T jet behavior (fix gluon PDF at large x)
- measure top mass with half current statistical error
- extra dimensions scale 1.6 TeV
- Measurement of B_s mixing

500 pb^{-1}

- signals for WW, WZ production
- observe radiation zero in $W\gamma$ process
- signals for technicolor?

1 fb^{-1}

- ~1000 top events per experiment
  - ~100 dilepton, ~800 lelpton + jets with b-tag
- start to see single top signal
- signals for SUSY in trileptons or jets+Missing E_T?
- signals for gauge mediated SUSY (photons +Missing E_T)?
- SUSY Higgs (4b jet) signal for m(A) ~ 100 GeV, tan β = 35

2 fb^{-1}

- SUSY in chargino/neutralino (trileptons) up to m(χ)=180 GeV (tan β =2)
- SUSY in squarks/gluinos (jets+Mmssing E_T) up to m(gluino)=400 GeV
- measure top mass to 2.7 GeV/expt
- observe spin correlation between top pair (exclude spin=0 stop)
- extra dimensions with a scale of 2.0 TeV
- measure W mass at level needed to improve on LEP (30 MeV per experiment)
- 95% exclusion of SM Higgs for mass =115 GeV

5fb^{-1}

- 95% exclusion on SM Higgs up to 125 GeV.
- 95% exclusion of all MSSM Higgs parameter space (maximal mixing)
- SUSY Higgs (4b jet) signal for m(A) ~ 150 GeV, tan β = 35

8 fb^{-1}

- 3 sigma evidence for SM Higgs mass = 115 GeV
- 3 sigma evidence for H -> WW around 160 GeV
- 95% exclusion for SM Higgs up to 130 GeV and 150-180 GeV

15 fb^{-1}

- 4-5 sigma signal for SM Higgs mass=115 GeV
- 95% exclusion for SM Higgs over all range up to 185 GeV
- SUSY Higgs (4b jet) signal for m(A) ~ 200 GeV, tan β = 35
- SUSY trilepton signal extended to large tan β and gluino masses 600-700 GeV
- measure top mass to 1.3 GeV/expt
- measure W mass at the level of 15 MeV/expt

Complementarity with LHC

- The Physics goals of the Tevatron and the LHC are not very different, but the discovery reach of the LHC is hugely greater
  - SM Higgs:
    - Tevatron < 180 GeV LHC < 1 TeV
  - SUSY (squark/gluon masses)
    - Tevatron < 600 GeV LHC < 2 TeV

Despite the limited reach, the Tevatron is interesting because both Higgs and SUSY "ought to be" light and within reach

- For Standard Model physics systematics may dominate:
  - Top mass precision
    - Tevatron ~ 1-2 GeV LHC ~ 1 GeV?
  - m_W precision
    - Tevatron ~ 20 MeV? LHC ~ 20 MeV?

Conclusions

- For as long as I have done high energy physics, the highest priority of the field has been to explore experimentally the question of EW symmetry breaking and TeV-scale physics
- That is about to change dramatically: the next few years will see the Higgs and/or SUSY become a discovery or set of discoveries to be understood and measured
  - and, we hope, the first window on to a new domain of physics at the TeV scale
- Personally, I can't wait to see what's behind the curtain